Emissions Reduction in Compression Ignition Engine

A Method for At-The-Source Reduction of Emissions

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A thesis submitted in partial fulfillment of the requirements for the degree of

BE Mechanical Engineering

Thesis Supervisor:

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Thesis Supervisor's

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Declaration

We certify that this research work titled “Emissions Reduction in Compression Ignition Engine” is our own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Copyright Statement

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Dedicated to our exceptional parents whose tremendous support and cooperation led us to this wonderful accomplishment

Abstract

In order to comply with the very definition of sustainability we have to ensure that the natural resources pass on to the next generation with minimal or no degradation or deterioration. Pollutants inhibit this transfer of resources to a large degree. That is why international societies like EPA are implementing stringent laws for the production of these pollutants. Road vehicles contribute a large chunk in environment pollution.

Diesel Engine emissions are much more complex and expansive to cater for as compared to the Gasoline Engines. Selective Catalytic Reduction and Exhaust Gas Recirculation are some of the methods widely implemented to reduce diesel engine emissions. In this project we devised a way for at the source reduction of emissions to inhibit the production NOx in the first place.

A water/air mist with a water flow rate of less than 10% of the air intake flow rate of the engine was injected in the intake manifold to test our research. We tested the emissions at various points and according to our experiment we had a maximum percentage decrease of 23% of the NOx production rates.

Key Words: *Diesel Engine, Water Injection, Emissions Control*

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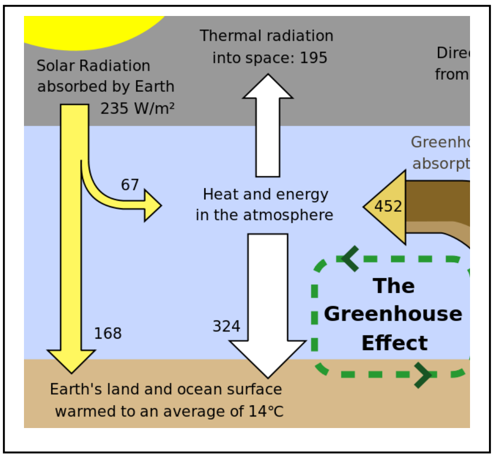
Chapter 1: Introduction to IC Engines and NOx Emissions

1.1 INTRODUCTION:

As soon as a discernible increase in the global temperature began bothering the human life, international societies began to implement certain laws to ensure the sustainability of the environment and to comply with the very definition of the sustainable that is to ensure the *transfer of resources to successive generation without or with minimal degradation or deterioration*. Smoking chimneys and gusting road vehicles made the top concerns of Environment Protection Association (EPA) to develop and implement these standards. The Clean Air Act requires EPA to set national ambient air quality standards for “criteria pollutants.” Currently, nitrogen oxides and five other major pollutants are listed as criteria pollutants. The others are ozone, lead, carbon monoxide, sulfur oxides, and particulate matter. The law also requires EPA to periodically review the standards and revise them if appropriate to ensure that they provide the requisite amount of health and environmental protection and to update those standards as necessary.

Some of these gases are also included in the list of greenhouse gases. Greenhouse gases are the one capable of absorbing and emitting infra-red wavelengths of light if present in atmosphere. These gases are the fundamental cause of the greenhouse effect putting its share in the global warming. Without these gases earth surface would average about 33 C colder than the present temperatures. These gases are listed as



1. Water vapor
2. Carbon dioxide
3. Methane
4. Nitrous oxide
5. Ozone
6. CFCs

It was back in the 1980s that the international society started focusing on the large chunk of pollution that the highway vehicles are causing and for that matter they developed certain standards. European standards [9], categorized from Euro 1 to Euro 5 and now the most recent Euro 6, are the bins that defines the average emissions of highway vehicles in grams that they produce per kilometer or per kilowatt-hour and these are the most widely accepted standards in the world.

Compounds that account for the emissions in internal combustion engines are NOx, PM and CO. Emissions manipulation is far less complicated and inexpensive in spark ignition engines than in compression ignition engines, since the operating pressures and temperature are lower. After treatment of exhaust gases with 3-way-catalytic converters effectively reduces the NOx by 99.5% well below the discernible rate for a sensor. The after treatment of exhaust gases for diesel engine proves to be much more complicated and complex with Selective

Catalytic Reduction, NOx traps and PM traps. For this reason at the source reduction of emissions methods are part of the modern research. EGR is a widely used technology for this but it comes with a tradeoff between NOxs and PM.
NOx are mainly controlled by lowering the peak combustion temperature that occur as the fuel burns in the combustion chamber. In order to control these temperatures we opted to inject an atomized spray of water in the intake manifold of a 6 cylinder inline diesel engine. This engine was designed to drive a HINO truck and the spray quality should be such that it does not condense at any bends in the manifold. The engine was mounted on the Taylor dynamometer test bed and all the values for brake torque rpm and NOx rates are measured.

1.2 Nitrogen Oxides:

NOx results from the combustion processes of motor traffic, power production, and the burning of wood and refuse. Tobacco smoking, use of gas-fired appliances, and oil stoves are also sources. Non-combustion processes include the fertilizer industry, manufacturing of nitric acid (HNO3), welding processes, and the explosives industry. Natural sources of NOx emissions include bacterial action, volcanic action, and lightning. These sources far outweigh those generated by human activity, but because they are distributed over the entire surface of the earth, their background atmospheric concentrations are very small.

1.3 Health Effects:

The sum of nitric oxide (NO) and NO_2 is commonly called nitrogen oxides or NOx. Other oxides of nitrogen including nitrous acid and nitric acid are part of the nitrogen oxide family. While EPA’s National Ambient Air Quality Standard (NAAQS) covers this entire family, NO_2 is the component of greatest interest and the indicator for the larger group of nitrogen oxides.

- Current scientific evidence links short-term NO_2 exposures, ranging from 30 minutes to 24 hours, with adverse respiratory effects including airway inflammation in healthy people and increased respiratory symptoms in people with asthma.
- NOx react with ammonia, moisture, and other compounds to form small particles. These small particles penetrate deeply into sensitive parts of the lungs and can cause or worsen respiratory disease, such as emphysema and bronchitis, and can aggravate existing heart disease, leading to increased hospital admissions and premature death.
- Acid Rain - NOx and sulfur dioxide react with other substances in the air to form acids, which fall to earth as rain, fog, snow or dry particles. Some may be carried by wind for hundreds of miles. Acid rain damages; causes deterioration of cars, buildings and historical monuments; and causes lakes and streams to become acidic and unsuitable for many fish
- Ozone is formed when NOx and volatile organic compounds react in the presence of heat and sunlight. Children, the elderly, people with lung diseases such as asthma, and people who work or exercise outside are at risk for adverse effects from ozone. These include reduction in lung function and increased respiratory symptoms as well as

respiratory-related emergency department visits, hospital admissions, and possibly premature deaths.

Considering the aforementioned reasons we opted to control these emissions of NOx in the first place that is we do not let them produce (at the source reduction)

1.4 Basics of Internal Combustion Engine:

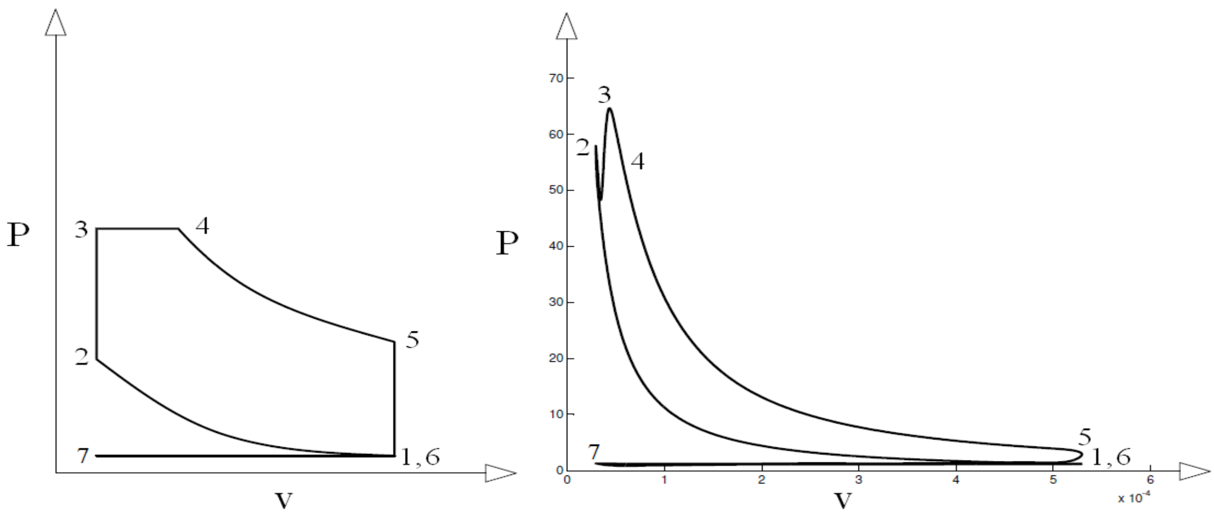
Internal combustion engines are typically a reciprocating piston cylinder assembly. IC engines are used to convert the chemical energy of the fuel into mechanical energy usually in the form of a rotating shaft. In automotive application this rotating shaft provides the power to the axles so that the wheels rotate to move the vehicle.

In a typical IC engine air fuel charge is brought into the cylinder and compressed until the piston reaches the TDC. At this point if the engine is spark ignition; a spark plug provides an electric arc that serves the purpose of initiating the combustion process otherwise if the engine is compression ignition this process starts of automatically at a specific pressure. As the air fuel charge combusts it expands and pushes the piston to BDC and hence producing work.

Details about the working of Diesel Engine:

Following is the list and graphical representation of all the process that govern the diesel cycle

IDEAL DIESEL CYCLE	ACTUAL DIESEL CYCLE
• Compression 1-2 • Heat Addition 2-4 • Expansion 4-5 • Heat Rejection 5-6 • Gas Exchange 6-7-1	• Compression 1-2 • Combustion 2-4 • Expansion 4-5 • Exhaust 5-6 • Fresh Intake 6-7-1

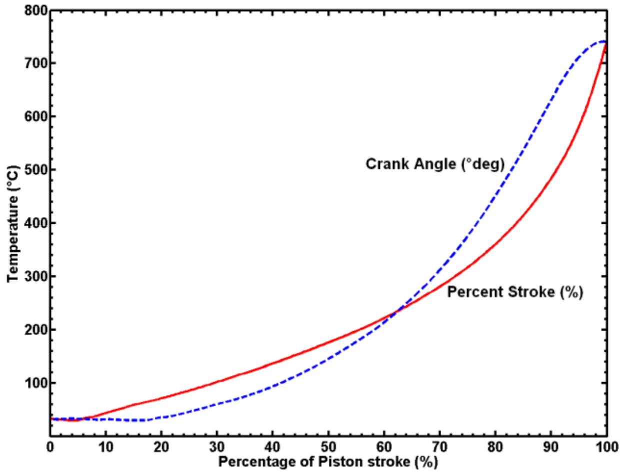


Theoretical and actual measured Diesel cycle pressure-volume diagram traces

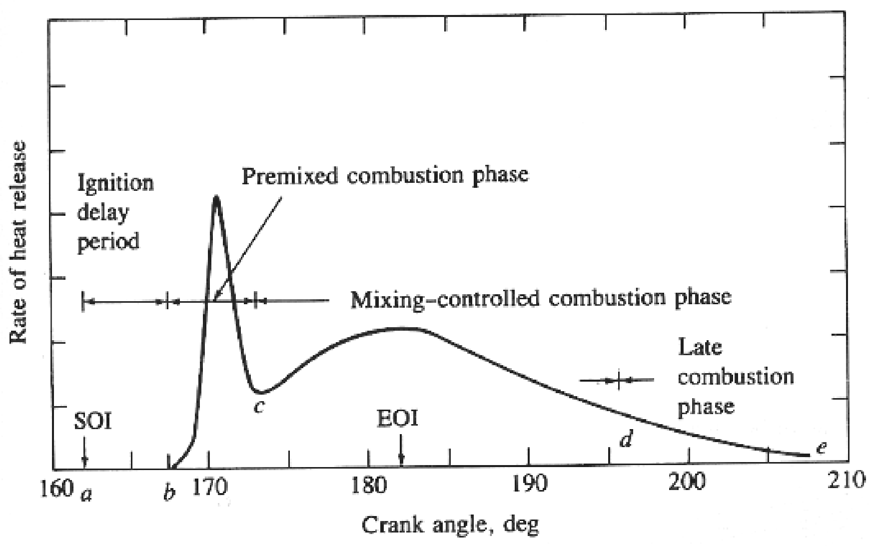
In order to fully understand the production of emissions and to control them we first have to have a complete understanding of the combustion process that is governing the production of these gases.

1.5 Understanding the Combustion Process:

The combustion process starts with the ignition of the air fuel charge. The energy from this ignition in compression ignition engine comes with the compressions of the air fuel charge to a point where it temperature rises to a sufficient level (of the order 600) to cause auto inflammation. These temperatures are obtained by producing the pressure ratios of the order 12:1 to 24:1. This pressure ratio is a function of swept volume, shape of the combustion chamber and the type of intake induction either forced (Turbo or Super charged) or naturally aspirated.



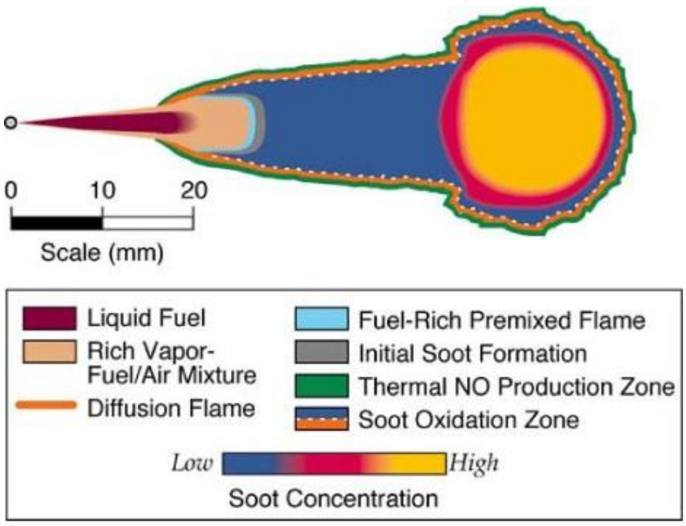
The combustion process can be better understood with the following rate of heat release diagram



The combustion process can be divided into four stages:

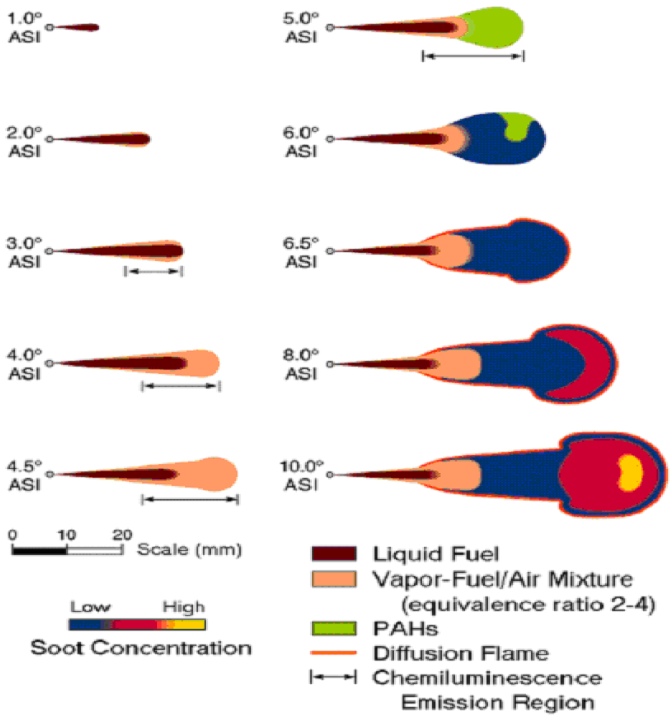
a. The first stage where the fuel is injected into the combustion chamber. The fuel injector injects fuel at high pressure into the heated air charge. The high relative velocity of the fuel jet against the air charge causes the fuel droplets to atomize. This atomization also aids in the mixing of the fuel droplets with the air, evaporating the fuel in the process. These evaporating droplets start to move away from the core of the jets. An air / fuel mixture has thus started to form and the high temperature encourages the reaction of the mixture even though no appreciable energy is released. Ignition eventually starts to take place between the core and the outer fringes of the fuel jet / vapor envelope and the pressure in the cylinder thus starts to increase. The first phase of combustion thus ends. This phase is known as the **ignition delay** (ID).
b. In the second phase of combustion, the fuel that was injected burns quickly and a relatively large amount of heat is released. This can be seen in between points ***b*** and ***c***. in the first half, the fuel / air mixture burns quickly and then the intensity tapers off. This is known as the pre-mixed combustion phase.
c. In the third phase of combustion is the mixing-controlled combustion or diffusion combustion. Here, the combustion rate is controlled by the fuel injection itself. This can be seen in between the points ***c*** and ***d***.
d. The fourth phase of combustion continues well into the expansion stroke. This combustion phase may be a result of partially unburned fuel. A part of the fuel energy is present in the fuel-rich combustion products and soot which is released as better mixing takes place during the expansion stroke. The reaction processes taking place during this phase are much slower as the charge temperature falls. In, the combustion curve from point ***d*** to ***e*** is characteristic of this late combustion phase.

Following is the pictorial depiction of the diesel fuel spray as ignition starts.

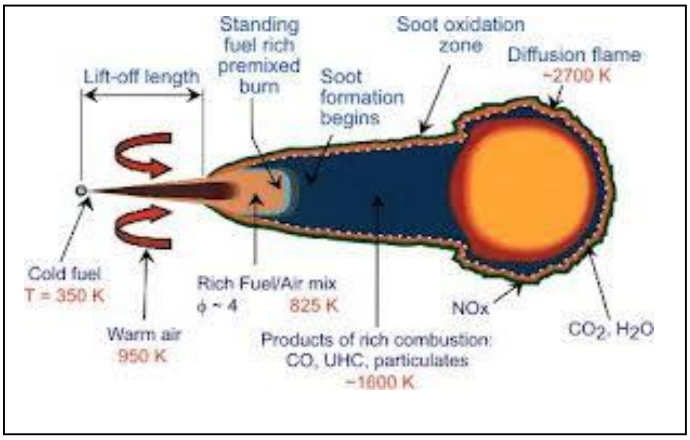


Quasi-steady Diesel combustion plume as presented by DEC (1997). Courtesy Dr. John E. Dec (Sandia National Laboratories).

Ignition delay starts just after the injection of the diesel fuel in direct injection diesel engines. Time based evolution of the flame front is shown in the following figure.



As the fuel is injected, the hot / compressed air entrapped in the combustion chamber is entrained by the fuel jet. This continuous entrainment of air into the fuel jet increases its temperature, and imparts heat energy to help the fuel vaporize. This vaporized fuel exists as an envelope around the fuel jet and the temperature starts to rise to 750 K and basic chemical reactions start to take place. Heat produced from these reactions and the further entrainment of hot air into the fuel jet increases the temperature to around 825 K. At these temperatures, basic oxidation reactions commence. According to Dec et al., the chemical products at this stage are largely composed of C_2H_2, C_2H_4, C_3H_3, CO and H_2O. The short-chain fuel components are the basic building blocks of polycyclic aromatic hydrocarbons (PAH) that lead to the production of soot. During these reactions, the temperature in the fuel jet increases to around 1600 K. These hot combustion products are pushed out by the fuel jet and then re-entrained in to the jet with the hot air in the cylinder.



1.6 Fundamentals of NOx Generation:

Atmospheric nitrogen proves to be the main source of the NO production in internal combustion engines. This nitrogen under suitable conditions of pressure and temperature oxidize to form the nitrogen oxide compounds. Following are the categories of NO produced in the internal combustion engines.

a. Nitrogen Oxides formed as a result of the reaction between atmospheric Nitrogen and Oxygen at high temperatures is called **Thermal NO**.
b. Nitrogen Oxide can also be formed by the Nitrogenous content in fuel and is called the **Fuel NO**.
c. Nitrogen Oxides formed as a result of the "fast" conversion of atmospheric Nitrogen and Oxygen in the flame front during combustion is called **Prompt NO**.
d. Nitrogen Oxides formed as a result of an intermediate reaction of N_2O production is called **Nitrous NO**.

The three primary sources of NO_x in combustion processes:

- thermal NO_x
- fuel NO_x
- prompt NO_x

Thermal NO_x formation, which is highly temperature dependent, is recognized as the most relevant source when combusting natural gas. Fuel NO_x tends to dominate during the combustion of fuels, such as coal, which have a significant nitrogen content, particularly when burned in combustors designed to minimize thermal NO_x. The contribution of prompt NO_x is normally considered negligible. A fourth source, called *feed* NO_x is associated with the combustion of nitrogen present in the feed material of cement rotary kilns, at between 300° and 800 °C, where it is also a minor contributor.

1.7 Thermal NOx:

Thermal NO_x refers to NO_x formed through high temperature oxidation of the diatomic nitrogen found in combustion air. The formation rate is primarily a function of temperature and the residence time of nitrogen at that temperature. At high temperatures, usually above 1600 °C (2900 °F), molecular nitrogen (N_2) and oxygen (O_2) in the combustion air disassociate into their atomic states and participate in a series of reactions.

The three principal reactions (the extended Zeldovich mechanism) producing thermal NO_x are:

$$N_2 + O \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$
$$N + OH \rightarrow NO + H$$

1.8 Fuel NOx:

The major source of NO_x production from nitrogen-bearing fuels such as certain coals and oil, is the conversion of fuel bound nitrogen to NO_x during combustion. During combustion, the nitrogen bound in the fuel is released as a free radical and ultimately forms free N_2, or NO.

Although the complete mechanism is not fully understood, there are two primary paths of formation. The first involves the oxidation of volatile nitrogen species during the initial stages of combustion. During the release and prior to the oxidation of the volatiles, nitrogen reacts to form several intermediaries which are then oxidized into NO. If the volatiles evolve into a reducing atmosphere, the nitrogen evolved can readily be made to form nitrogen gas, rather than NO_x. The second path involves the combustion of nitrogen contained in the char matrix during the combustion of the char portion of the fuels. This reaction occurs much more slowly than the volatile phase. Only around 20% of the char nitrogen is ultimately emitted as NO_x, since much of the NO_x that forms during this process is reduced to nitrogen by the char, which is nearly pure carbon.

1.9 Prompt NOx:

This third source is attributed to the reaction of atmospheric nitrogen, N_2, with radicals such as C, CH, and CH_2 fragments derived from fuel, where this cannot be explained by either the aforementioned thermal or fuel processes. Occurring in the earliest stage of combustion, this results in the formation of fixed species of nitrogen such as NH (nitrogen monohydride), HCN (hydrogen cyanide), H_2CN (dihydrogen cyanide) and CN- (cyano radical) which can oxidize to NO. In fuels that contain nitrogen, the incidence of prompt NO_x is especially minimal and it is generally only of interest for the most exacting emission targets.

$$CH + N_2 \leftrightarrow HCN + N$$
$$CH_2 + N_2 \leftrightarrow HCN + NH$$
$$CH_2 + N_2 \leftrightarrow H_2CN + N$$

$$C + N_2 \leftrightarrow CN + N$$

1.10 NO from N_2O:

At high pressures NO formation via N_2O becomes important:

$N_2 + O + M \rightarrow N_2O + M$
$N_2O + O \rightarrow 2\ NO$ (activation energy 97 kJ/mol)
$N_2O + O \rightarrow N_2 + O_2$

Competing Reactions:

$N_2O + O \rightarrow NO + N$ (thermal NO) $N_2O + O + M \rightarrow N_2O_2 + M$

1.11 Summary of all the Reactions:

Reaction	**Temperature range, K**
(1) $O + N_2 \rightarrow NO + N$	2000-5000
(-1) $NO + N \rightarrow O + N_2$	300-5000
(2) $N + O_2 \rightarrow NO + O$	300-3000
(-2) $NO + O \rightarrow N + O_2$	1000-3000
(3) $N + OH \rightarrow NO + H$	300-2500
(-3) $NO + H \rightarrow N + OH$	2200-4500

Chapter 2: Water Injection System

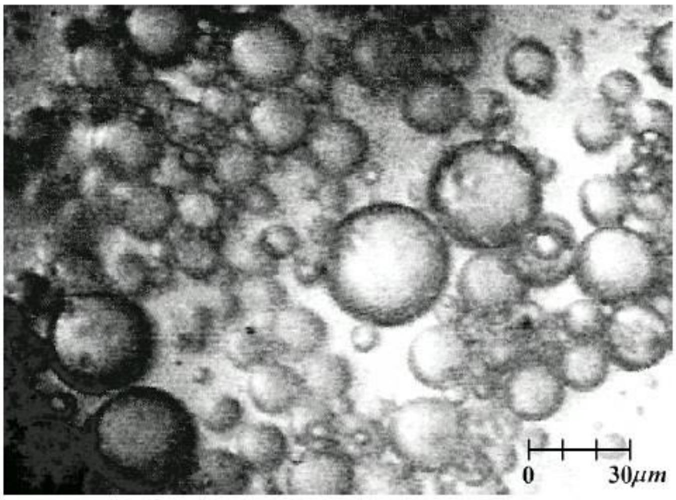
2.1 Types of Water Injection:

There are four main methods of water injection in a diesel which have been used and researched till date. They are stated and described in detail as follows:

1. Water / Fuel emulsion injection
2. Combustion chamber water injection
3. Stratified water injection
4. Intake manifold water injection

2.2 Water / Fuel Emulsion Injection:

Water / fuel emulsions are liquids which consist of the fuel, water, and an emulsifier. The type of emulsifier used depends upon the type of emulsion needed. Water / Fuel emulsions have been sold by companies like Shell, Chevron and BP.



Liquid structure of a 40% W/O diesel emulsion

Figure above shows a microscopic photograph of a W/O emulsion having 40% water by mass. This fuel was used in a Rapid Compression and Expansion Machine (RCEM) to evaluate the change in combustion performance with varying levels of W/O mix ratios. Subsequently, correlations were developed to correlate the change in NOx and PM formation levels.

In this mode of water injection, as the ratio of water to fuel is increased, the volume of mixture to be injected increases. We may increase the injection pressure to inject the required quantity of fuel in a given duration, or the injection duration may be increased to inject the same quantity of fuel.

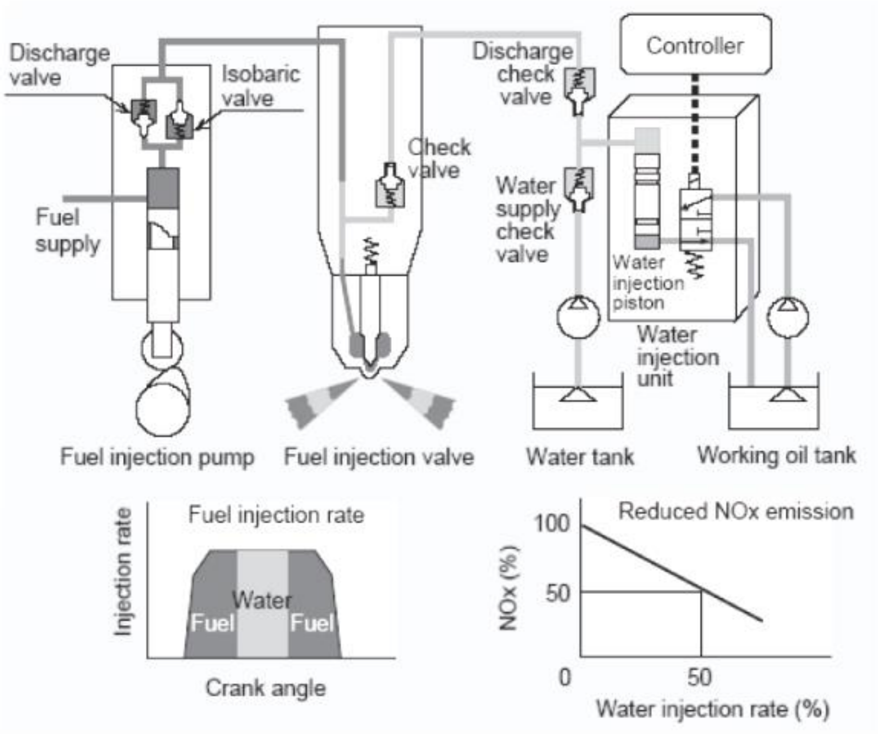
2.3 Combustion Chamber Water Injection:

In this type of water injection, there are two methods of injection in use. One system involves adding an injector for independent water injection alongside the fuel injector in the cylinder head. The second system involves changing the injector to one which has two needles – one to control the fuel flow, and another to control the water flow. Much higher pressure is needed in these systems as compared to the stratified fuel injection systems normally used. Its benefits over the fuel/emulsion system are that in this system, the fuel-water ratio can be changed and water injection timing can also be controlled. An example of a fuel/water injector is shown below.

Wartsila's direct water injection fuel injector

2.4 Stratified Water Injection:

Using the stratified water injection method, we can mix water and fuel just before injection into the cylinder. In this case, we need special injectors which have an inlet for high pressure water injection into the engine combined with diesel. A system developed by Mitsubishi Heavy Industries is shown below. Here, the injector is charged with a pre-determined quantity of water by a distribution system during the time the injector is not pressurized. The surplus diesel fuel in the injector is pushed into the spill circuit. When the injector is pressurized by the injector pump, the higher pressure diesel closes the water supply check valve and the water is injected into the combustion chamber as a spray via the fuel injector.



Mitsubishi Heavy Industries Stratified Water Injection

As compared to emulsion injection, the advantages of stratified injection are as follows:

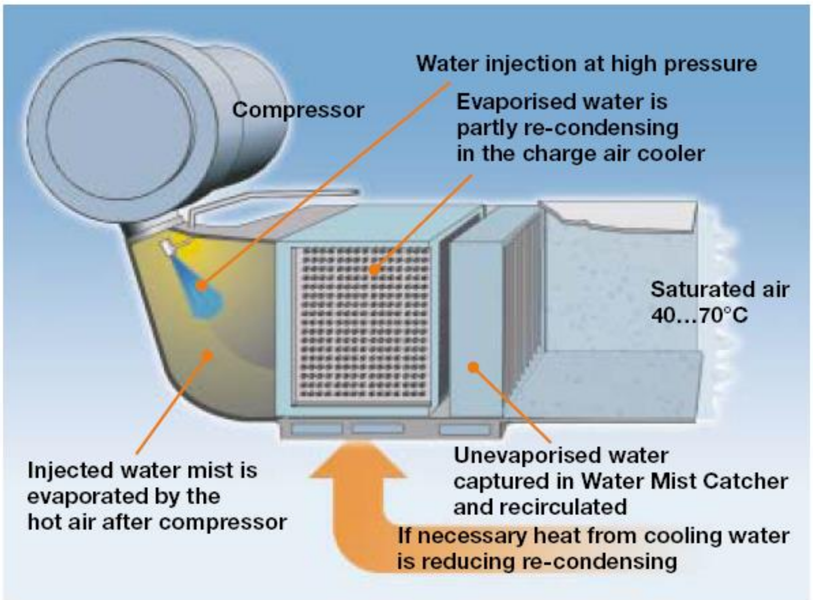
1. More precise control of water / fuel mix ratio.
2. Ability to vary water / fuel mix ratio.
3. Start and stop on neat diesel fuel without using a second fuel source
4. Combustion delay is shorter than for emulsion injection as the first part of the injection is pure diesel

A disadvantage is that this system is costlier than the emulsion injection system as a separate water metering system is required.

2.5 Intake Manifold Water Injection:

Here, water may be injected in liquid or vapor form into the intake manifold of an engine. Water injection may take place before or after the compressor. Liquid water injection may be continuous or pulsed. Water injection may be achieved via a single injector or via multiple injectors to ensure proper distribution to each cylinder.

In the case of the vapor injection, certain manufacturers have been working with unheated or heated water sprays in a large chamber through which intake air is passed. An example of such a system is shown below. Details are outlined in the following figure.



Wartsila's Combustion Air Saturation System (CASS)

2.6 Injector Design:

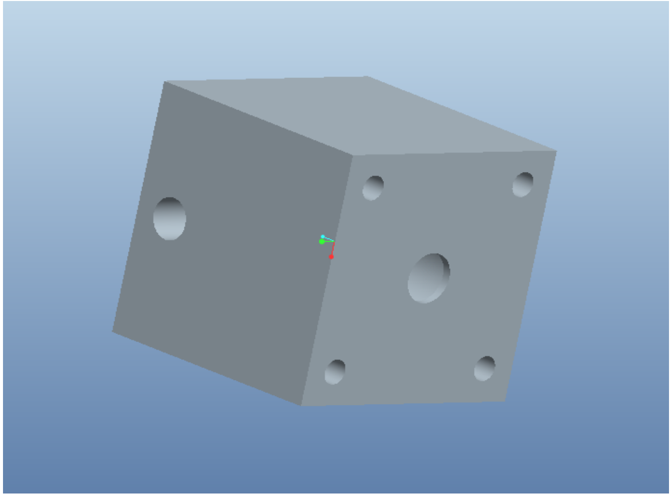
Final design consisted of the following components:

1. Injector Block
2. Injector Core
3. Nose Cone
4. Front Plate
5. M6 x 15 Bolts

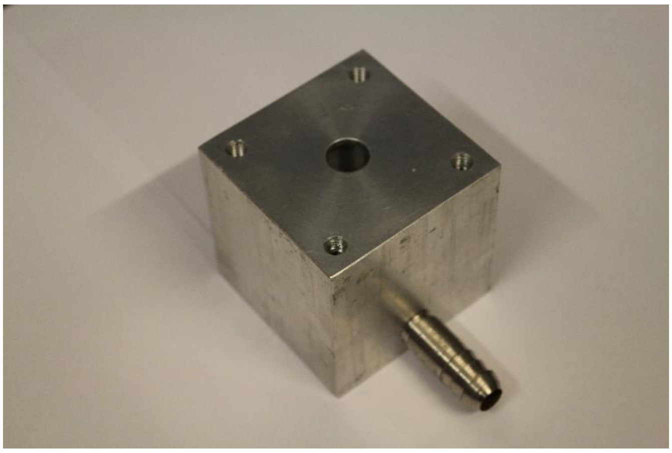
Each of these components' design is detailed below:

Injector Block:

The design for the main injector block was visualized in Pro Engineer. The material used was Aluminum. Machining operations were performed at MRC (Manufacturing Resource Centre). Facing of the sides were carried out on a milling machine while boring of wholes were done at a lathe machine. Below is a CAD model of the injector block. Refer to appendix for dimensions.



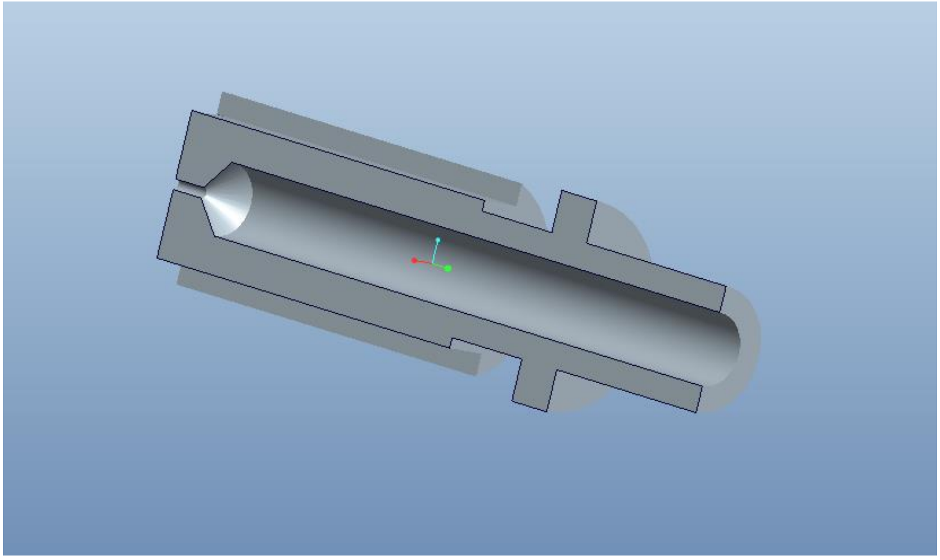
The finished block is shown below. It has a mild steel nozzle attached to it for water inlet.



Injector Core:

Initially, the injector was supposed to be extracted from a petrol fuel injector and used for the air pathway. The extracted core was to be supported at the center of the injector block by a vinyl tubing. However, during testing, the air flow through the core was not found up to the desired standards and the design was changed. The injector and the extracted core are shown below.

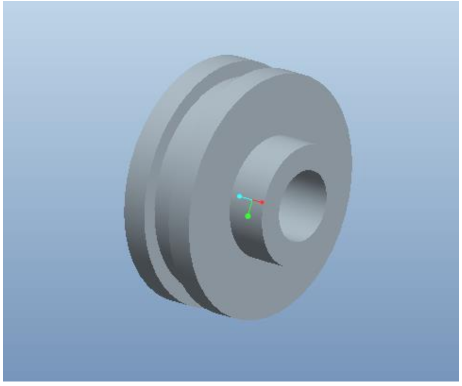
The new design was such that the metallic core form the injector was not required. A unique nylon core was designed and manufactured which had an air passage at the center and water passages at the sides. Nylon was the material of choice because it was found to be easily machined as we needed a 1mm hole at the end of the core for a very fine air jet. The CAD design is provided below. Refer to appendix for exact dimensions.



The finished part was tested and this time the air jet performed as desired and thus the core was fitted into the injector block. The machined part is shown in the following picture.

Nose Cone:

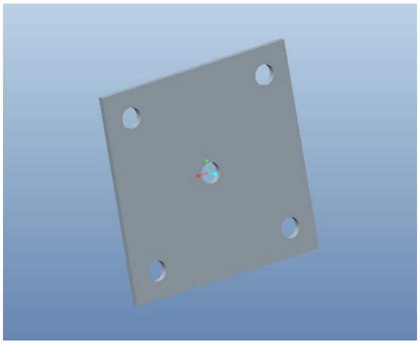
The nose cone is the end orifice through which an air/water spray emerges. It is manufactured from mild steel. It has a groove for an O-ring seal which stops leakages. The CAD design of the cone is shown below. Refer to appendix for dimensions.



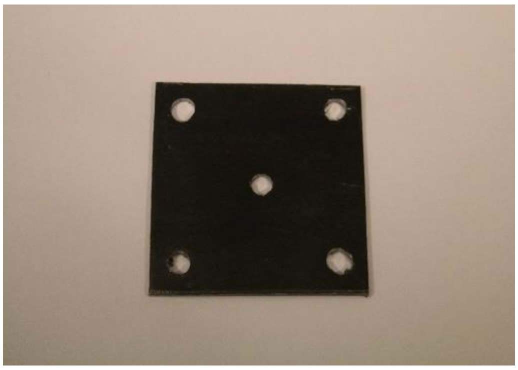
The machining of the part was difficult owing to the lack of a drill chuck able to hold a 1mm drill bit. Nevertheless, the part was machined according to dimensions and is shown below.

Front Plate:

The function of the front plate is to hold the nose cone in place. It is designed such that the film thickness of water at the nose cone can be varied by tightening or loosening the nose plate. It has been manufactured from a 2mm thick iron sheet. The holes were drilled using appropriate drill bits and filed to fit. The CAD model of the front plate is shown below.



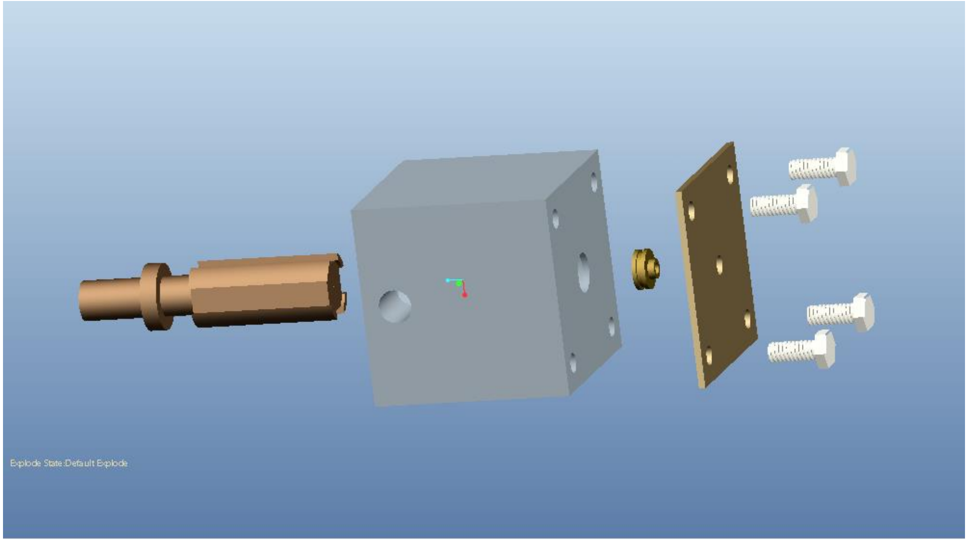
And the manufactured front plate is presented as follows.



M6 x 15 Bolts:

Four M6 x 15 bolts were used to secure the Front plate to the injector block. They are shown below.

Exploded View:



2.7 Water Injection Flowrate Control:

After designing the water injection kit, the next step was the controlling the flowrate through the water pump to achieve a fine quality of mist and also limit the water rate injection to safe limit. The maximum acceptable water injection rate was determined to be the 10% of engine air flowrate. The fuel pump being used in the injection as water pump is Positive Displacement Gear type pump which gives a constant volume flowrate at a given rpm no matter the discharge pressure. Following methods were considered to control the flowrate of pump:

- Pump Pulse Width Modulation (PWM)
- Pressure Regulator
- Arduino based Pump flow Control

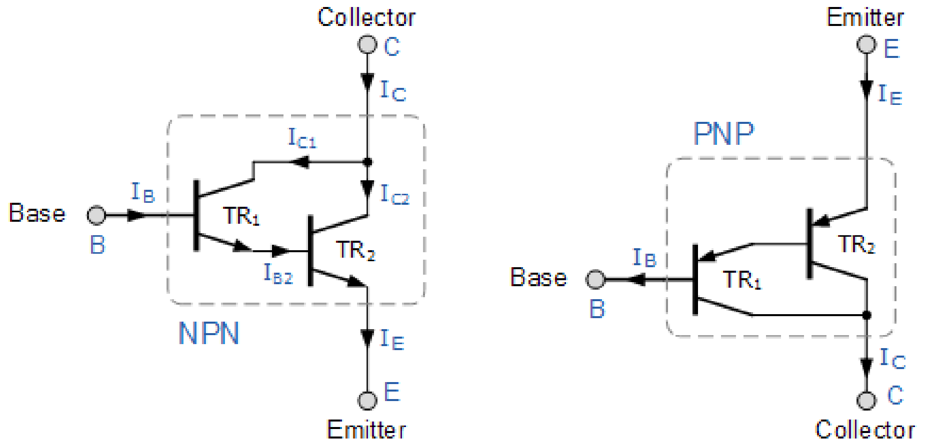
Pressure Regulator was not available at a suitable price. Using Arduino to control the flowrate required Arduino programming coupled with NI LABVIEW. Pump Pulse Width Modulation simply requires a power transistor being used a switch. Due to availability of the components and ease of control Pump PWM was selected as a most suitable method.

Pump Pulse Width Modulation:

Pulse width modulation is a technique in which the duty cycle of TTL pulse is varied according to the modulator. The main idea behind the Pump PWM was to measure the water flowrate at constant frequency and varying duty cycle. In this way Pump rpm can be varied along with the flowrate. The main circuit consists of the following components

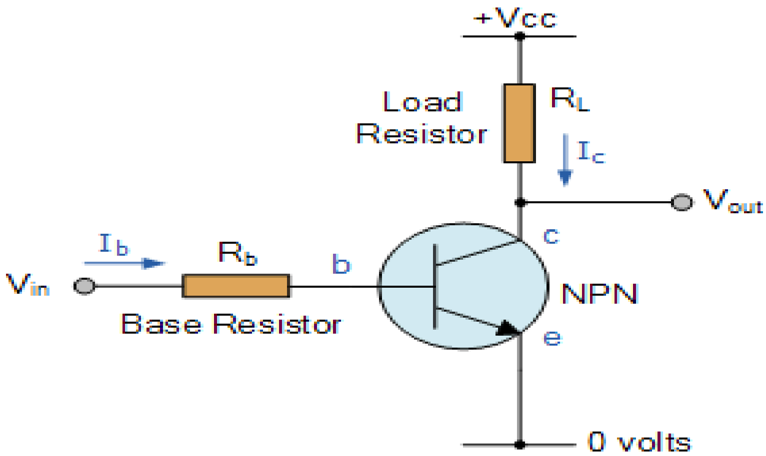
- TIP 142 Darlington NPN Power transistor
- Function Generator
- Fuel Pump
- 12V DC Battery
- 100Ω Base Resistor

As the name suggests Sidney Darlington invented a special arrangement of two standard NPN or PNP bipolar junction transistors (BJT) connected together **called as Darlington Transistor.** The Emitter of one transistor is connected to the Base of the other to produce a more sensitive transistor with a much larger current gain being useful in applications where current amplification or switching is required.



We used TIP 142 Darlington Power transistor for our circuit.

A TTL pulse of known frequency and duty cycle is provided at the base of npn transistor with the help of function generator. Transistor is acting as a switch. Emitter of the transistor is grounded and the load (fuel pump in our case) is placed between the collector and the battery. The circuit is shown below



Pump Flow rate Measurement:

After PWM of pump, the next step was to measure the flowrate and determine the suitable readings of duty cycle and frequency for our desired flowrate. The engine flowrate was determined theoretically. The power output of the engine is 85KW. According to theoretical method for 100KW power output the required engine air flowrate is 0.1kg/s. According to theoretical method the air flowrate of Hino EC 100 Engine is 0.085kg/s. Our objective was to design the kit for a maximum of 10% of the engine air flowrate. We conducted an experiment to measure the water flowrate coming out of the injector nozzle. The results are shown below.

Frequency (Hz)	Duty Cycle (%)	Air Pressure (bar)	Water Flowrate (kg/s)	Percent of the total Intake Air Flowrate (%)
500	30	6	0.00102	1.2
500	40	6	0.001275	1.5
500	50	6	0.0014875	1.75
500	60	6	0.0016575	1.95

2.8 Engine Air Intake Flow Calculations [10]:

Engine Model: Hino EC 100

RPM	2600
Intake air temperature	35 `C
Horse Power	76
Intake CFM	208
Exhaust Temperature (F)	900
Exhaust Flow CFM	524

Density of air at intake air temperature = 1.23 kg/m^3
CFM to kg/sec conversion:
1ft3 = 0.028317 m3
208 ft3 = 208*0.028317 = 5.88
This implies that intake mass flow rate is 5.88m3 /min
5.88*1.23/60 = 0.12054 kg/sec

Therefore we had an intake flowrate of 0.12054 kg/sec of air at 2600 rpm

CID of the engine = 305.1

Intake Flow Formula in CFM= (Engine Size (CID) x RPM / 3456) x Volumetric Efficiency

Using the above working the following sheet is developed using excel.

Engine Size	**RPM**	**Volumetric Efficiency**	**Air Intake CFM**	**CFM to Kg/sec for air at 25 (C)**
305.1	1000	0.6	52.96875	0.03074828
305.1	1250	0.65	71.72851563	0.041638296
305.1	1500	0.7	92.6953125	0.05380949
305.1	1700	0.75	112.5585938	0.065340095

Chapter 3: Experimental Setup

3.1 Industrial Collaboration:

The project was started initially with the collaboration of MAN Diesel & Turbo SE, Pakistan. Our project team went to Lahore in October 2013, to present two project proposals to the training head Mr. Sohail Ahmed. Depending on the feasibility of the project our proposal on Emissions Reduction through Water Injection in Diesel Engine was approved. The other proposal about the steam injection in gas turbines could not be approved due to unavailability of gas turbine for project purpose. Our group was promised an engine for testing. After 1 month Mr. Sohail Ahmed unfortunately got posted in Malaysia and the project was handed over to Service Manger Mr. Zulfiqar Ahmed. After completing the water injection kit design and fabrication, our team again went to Lahore to see the engine available for testing. The engine provided by MAN Pakistan was GENSET John Deere 4.5 liter Diesel Engine shown below.

We were given a time limit of next 20 days for testing. Exhaust Gas Analyzer previously promised by Mr. Sohail Ahmed was also not available there. The Exhaust Gas Analyzer available in SMME is integrated with the Dynamometer and is not portable. Our group tried to acquire an Exhaust Gas Analyzer from UET Lahore but no encouraging response came. Eventually we had to lose our industrial collaboration and the project was completed in SMME.

3.2 Engine Specifications:

Rebuilding the engine was the main and most difficult part of our project. The engine available to us was 5000cc Hino EC 100 Engine. Details of the engine are as follows:

Engine Model	HINO EC 100
Type	Diesel 4 Stroke, Vertical 6 Cyl., in-line, Valve in Head, Water Cooled
Bore & Stroke	97ϕ x 113 mm
Piston Displacement	5.01 liter
Compression Ratio	20.3 : 1
Firing Order	1-4-2-6-3-5
Startical Timing	18^o BTDC
Valve Clearance (Cold)	Intake 0.25mm Exhaust 0.25mm
Injection Nozzle Pressure	$120 kg/cm^2$
Engine Oil Capacity	12.5 liters
Cooling Capacity	27 liters
Thermostat Range	82^oC
Electrical Voltage	24 Volt Throughout
Standard Engine Oil Pressure	$1\text{-}5\ kg/cm^2$
Weight	Approx. 450kg

The engine was in disassembled form with every part needing proper cleaning before assembling.

3.3 Engine Cleaning:

First step was to clean each and every part of the engine so that engine gives the desired performance when assembled. The cleaning was performed in two steps. We used kerosene oil to clean every part of dust particles and lubricant oil. Then proper lubrication was applied to the parts where needed. Engine parts cleaned were

- Pistons and connecting rods
- Big end bearings
- Journal bearings
- Crankshaft
- Camshaft
- Engine head
- Oil sump
- Engine block
- Flywheel

- Timing gear
- Idle gear
- Valves rocker assembly
- Push rods
- Fuel Pump

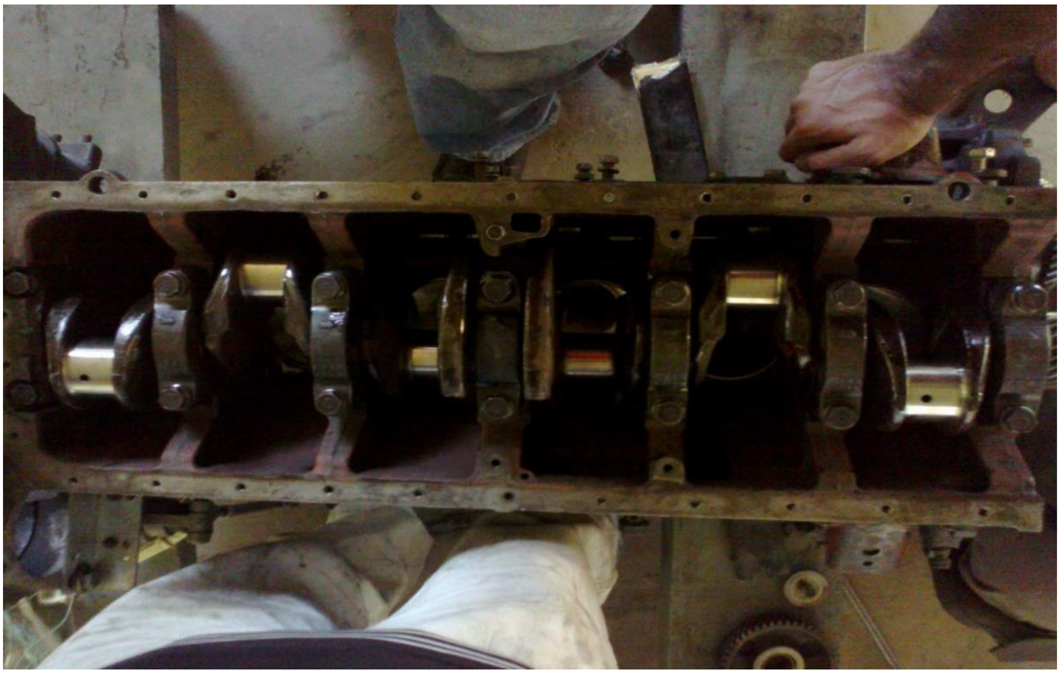
The head gasket of the engine needed to be replaced. So our group went to Rawalpindi and bought a new head gasket of the engine. A picture of some of the cleaned parts is shown below.

3.4 Engine Assembling:

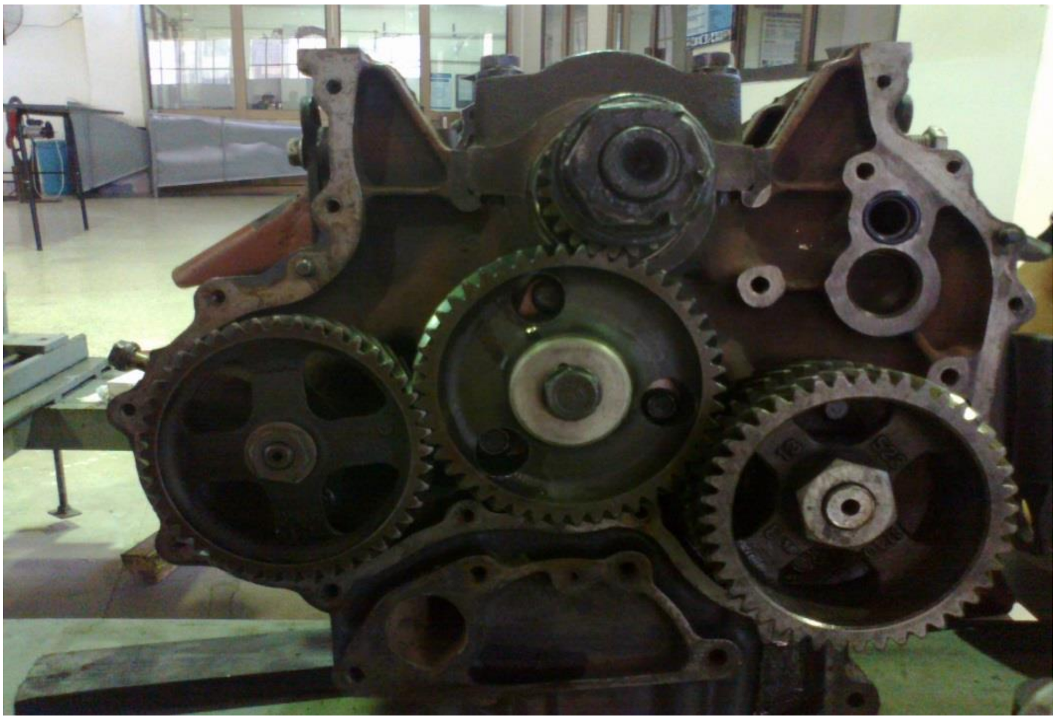
After cleaning the engine our group took on the task of assembling the engine along with the lab technician Fazal Badshah. We first read the engine manual thoroughly to determine the required torques for each bolt and standard method of assembling every component. The engine assembly took us almost two weeks but it was a very useful practical learning experience.

We started off by placing the crankshaft in the engine block. The crankshaft is precision die stamp-forged combined with counterweights. There are seven main bearings, the one in the center also functioning as a thrust bearing. Journals and crankpins are induction hardened and thick to provide strength and wear resistance. The crankpin is hollow to decrease weight and minimize centrifugal force effect. It is lubricated from the crankshaft bearings through a copper pipe inside the crankshaft. The thin kelmet crankshaft bearings are lined with steal on the back and are lead plated. After proper aligning of crankshaft the bearing caps were tightened with the help of torque wrench. The bolts were tightened from center to end in counter-clock wise fashion with the standard torque of 80-83 lb ft.

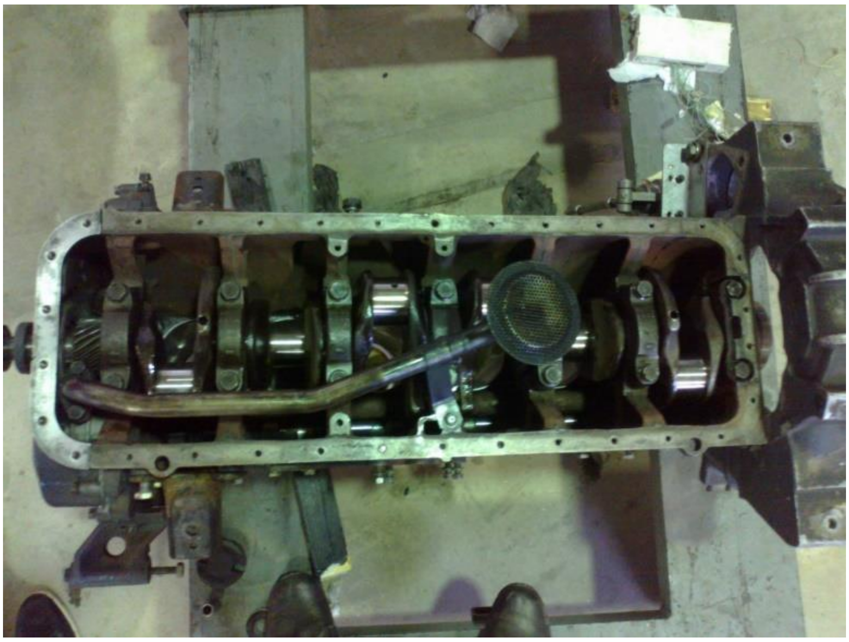
The assembled picture of crankshaft in the engine head is shown below.



After assembling the crankshaft we attached the idle gear, timing gear, pump gear, oil pump gear and crankshaft gear with proper arrangement of timing as written in the manual as shown below.



The next step was the placement of oil suction strainer to the engine block as shown.



After attaching the oil pump to the engine, the engine needed to be repositioned to place the pistons and connecting rods in the cylinder liners. We used a hydraulic lift crane to lift the engine and position it properly as shown below.

Placing the pistons in the cylinder liners was the most important step as proper arrangement of pistons rings is very important for the lubrication. Also direction of cylinder head and position of inlet and exhaust valve needs to be kept in mind. Beginning with No.1 ring in the top, all the 5 rings should be installed in numerical sequence, numbers should be faced up. With the rings installed, the piston is inserted in the cylinder. The clearance of the ring should positioned so that it is 120⁰ opposite that of the preceding ring. Also the ring side clearance should not face in the direction in which the piston presses the liner during combustion. A piston ring compressor was used to after arranging the piston rings to keep the arrangement intact while forcing the piston in the cylinder. After applying the proper lubrication the pistons were placed in every cylinder and the connecting rod bearing caps were tightened with the help of torque wrench according to specified torque of 58-72 lb ft.

Oil sump was attached after applying silicon at the edges for sealing. Then we replaced the engine so that cylinders were facing upward for placing head gasket and engine head. After that we attached all the auxiliaries like fuel pump, oil pump, oil filter, fuel filter, alternator, etc. The oil pump is located on the middle of the engine left side. It is driven from camshaft by a helical gear. Both outer and inner rotors are special casting products. The fuel feed pump draws fuel from the fuel tank. The fuel passes through the fuel filter and is fed to the fuel injection pump. The injection pump forces the fuel under high pressure through the injection lines to the nozzles where it is injected into the pre combustion chambers. Some fuel reaching the nozzle lubricates the nozzle head. After lubricating, it returns to the tank through the leakage pipe. On the injection pump, a governor and timer are installed. The governor controls the idling speed and maximum speed of the engine, the timer adjusts the fuel injection timing. After placing the camshaft in the engine block, the next step was the placement of head gasket and engine head. The cylinder head is shown below.

After placing the head gasket and pushrods, the engine head was placed on the engine. The bolts were tightened from the center to the ends clockwise fashion to a maximum torque of 123-130 lb ft. Then valve rocker assembly was placed. The main engine assembly was complete after it. Some other parts like exhaust manifold, flywheel, timing belts, water pump, water header, crankshaft pulley, etc were attached.

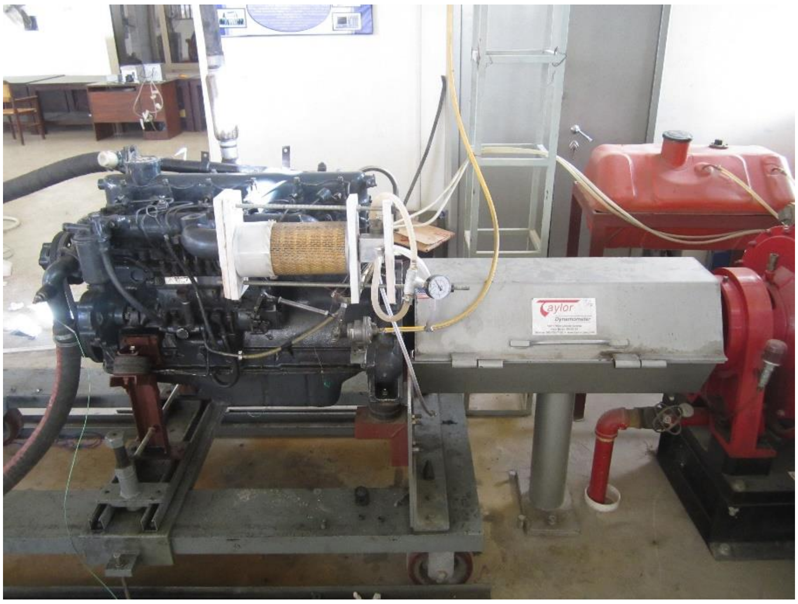
During the whole assembling, proper sealing through silicon was maintained. The complete assembled EC 100 Hino Engine is shown below.

The next section deals with the mounting of the engine on Dynamometer for testing.

3.5 Dynamometer:

The EC-100 engine was mounted on a DX-33 Taylor Dynamometer. It has the ability to generate 750hp power and 2413 ft-lb torque at 4000 rpm. The dynamometer incorporated a pneumatic starter motor to start the engine after which the engine ran self-sufficiently. The dynamometer's electronic control system also provided the facility to vary the throttle pneumatically and keep it constant at a known rate; a feature which was used extensively during testing. A picture of the dynamometer is shown below.

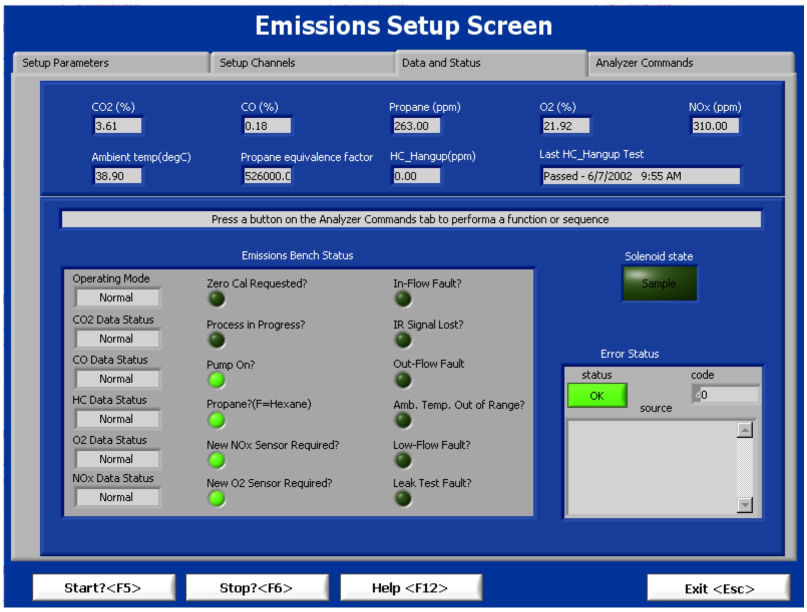
The engine, mounted on the engine cart, was coupled with the dynamometer via a driveshaft connected at the fly wheel.



3.6 5-Gas Emissions Analyzer:

The emissions analyzer is a measurement unit to meter the amount of various gases in the exhaust of the engine. A probe is inserted into the exhaust of the engine which is connected to the data acquisition unit and takes readings of Oxygen, Carbon Dioxide, Carbon Monoxide, NOx and Propane. These readings are displayed visually through the dyno software.

A sample reading is shown below.

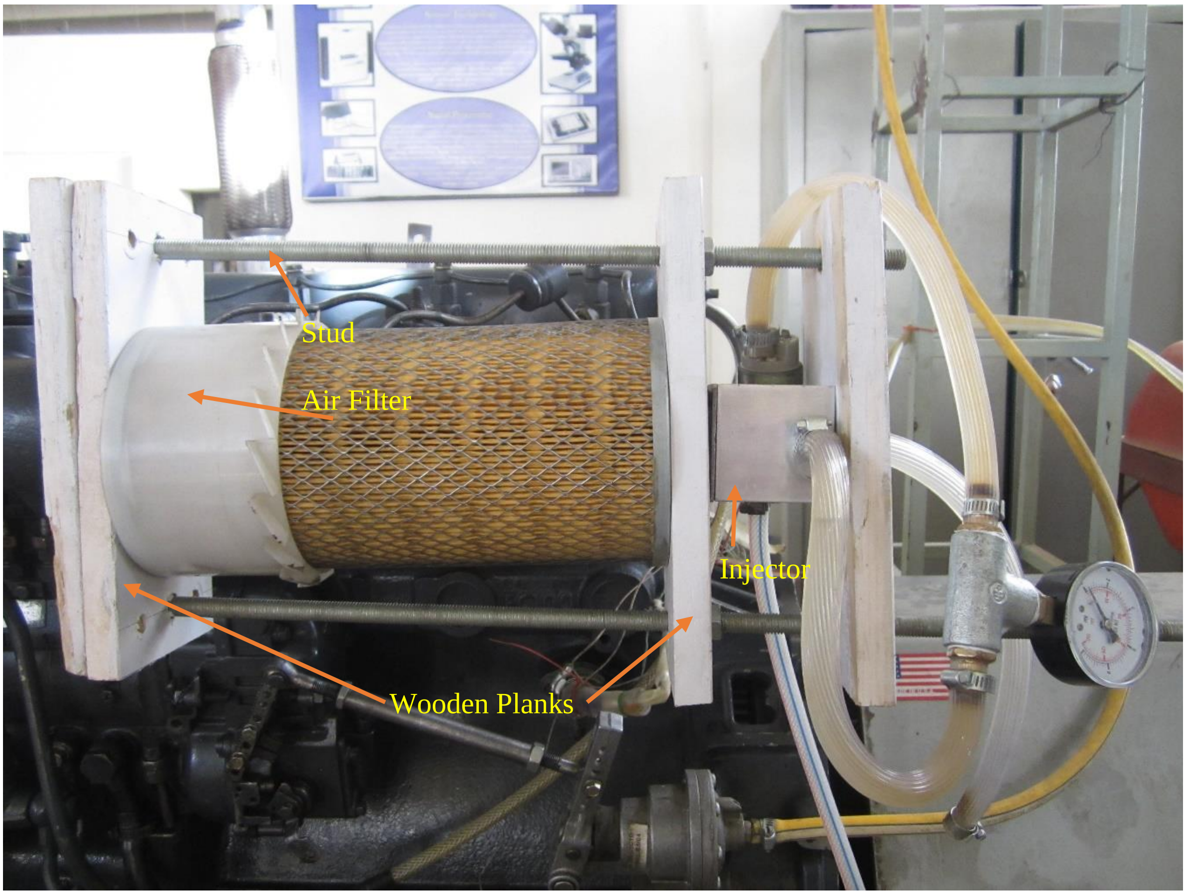


The 5 Gas Analyzer box is shown below.

3.7 Injector Mounting:

The water injector was mounted on the air intake of the engine. A support assembly was designed and manufactured which was attached to the air intake pipe. The assembly could hold the air filter and the injector in line with the air intake pipe. The said assembly was made from blocks of wood attached together by two 18 inch long studs.

Compressed air required for the injector was taken from a compressed air line for the dynamometer. Water supply was taken from a tap near the test location. The motor was run on a 12 V battery. The assembly as mounted on the engine is shown below.



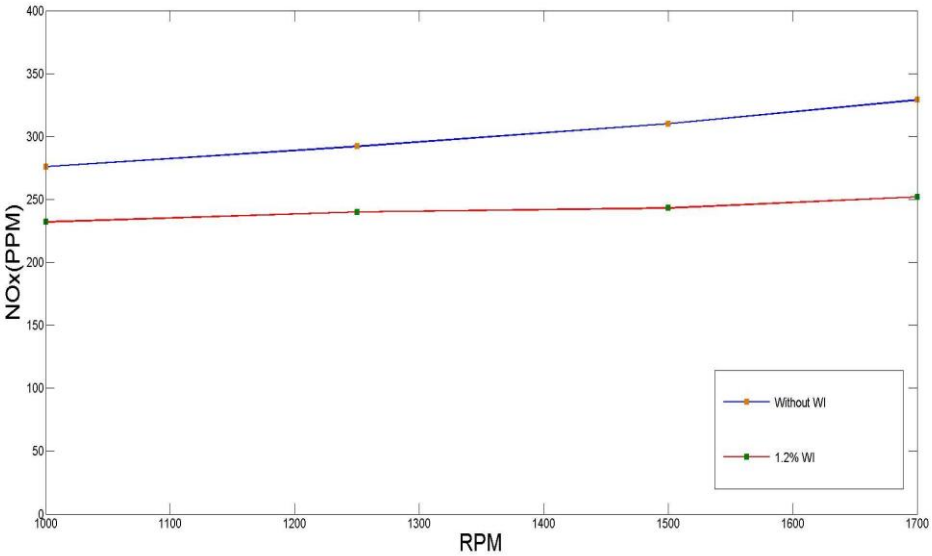
Chapter 4: Studying the Effects of Water Injection

4.1 Testing and Results:

Engine was started using the pneumatic motor of the Taylor Dynamometer. A pressure of 6 Bar was supplied through the air compressor. The engine was run at idle until the coolant temperature reached 70^{o}. The testing was designed to acquire NOx emission values at 1000, 1250, 1500 and 1700 Engine RPM. First phase of the test consisted of acquiring the required values without water injection. Engine was run at each RPM for about 5 minutes to get a stable reading. The probe of emission analyzer was inserted in the exhaust outlet and stable reading at each rpm was noted. The engine was shutdown to prepare it for the second phase of the testing. Second phase was to determine the NOx emission values with 1.2% water injection at above mentioned engine RPMs. Again the engine was run at idle for some time until the coolant temperature reached 70^{o}. After that the injection was started, engine was run at each RPM for about 5 minutes to get a stable reading. After completing the testing, water injection was stopped and engine was run at 1700 RPM for about 10 minutes to vaporize any water droplets left in the engine.

The test results are as follows:

Engine RPM	NOx(PPM) Without WI	NOx(PPM) 1.2% WI	Percentage Decrease
1000	276	232	15.8%
1250	292	240	17.67%
1500	310	243	21.46%
1700	329	252	23.19%



As the engine rpm increases, percentage decrease in the NOx also increases. The prime reason behind it is the reduction in temperature which can be explained by following points:

- Cooling effect due to vaporization of water
- Heat capacity increases due to increase in the intake charge mass
- Delay in combustion due to delay in ignition

NOx production can further be reduced with increase in water injection but ignition delay and combustion stability puts a limit to water injection.

4.2 Possible WI Problems and Their Solution:

Ignition Delay increases as the rate of water injection increases. The problem can be solved by adjusting the fuel injection timing accordingly.

Rate of heat release decreases with water injection for low loads. At higher loads, the effect is negligible. As WI is most suitable for the engines operating at constant high load like truck engines, etc so the problem is negligible at that level.

BSFC is expected to increase and engine torque is expected to decrease at low load due to decrease in ROHR and in cylinder pressure. As at higher loads the effect of WI is negligible on ROHR so its effect on BSFC and engine torque is also negligible.

Conclusion:

The first chapter aims to provide the basic understanding of the NOx production and why limiting its production is of high importance. This chapter provides a detailed thermodynamic study of the diesel engine working and how the combustion takes place inside the cylinder.

In the second chapter we presented our research for the developed technologies in this field and provided a detailed implementation of these technologies. We theoretically analyzed each technique to develop our injector for the intake manifold water injection. All of the techniques had there pros and cons but injecting water in the intake manifold involved minimum intervention in the engine and proved to feasible for developing a commercial product.

In order to carry out the gap analysis we had to develop an experimental setup that we did and discussed in the third chapter. We assembled the engine in bits and bytes from the scrap and made it running. Then we coupled it with a dynamometer for data acquisition for our results.

Finally in the fourth chapter we present our result to be reasonably good.

FUTURE PROSPECTS:

The method we developed is of great application in static engines used for power generation or for ship engines having high values for swept volume. If somehow we are able to condense the water vapor in the exhaust and extract its heat we can also run a bottoming-cycle power generation cycle with this method.

Following may prove to be some interesting research areas

- To study the effect of water injection on the overall reliability and life of engine.
- To study the contamination of engine oil due to water injection especially for engines in which forced induction is employed.
- To model the effect of water injection on the PM production rate.
- To study the effect of water injection on the lift off length.

References:

[1]http://www.epa.gov/oaqps001/nitrogenoxides/health.html

[2]http://www.extraordinaryroadtrip.org/research-library/air-pollution/understanding-air-pollution/nitrogen-dioxide/health.asp

[3]http://www.unep.org/tnt-unep/toolkit/pollutants/nitrogen.html

[4]http://dc352.4shared.com/doc/ry0UMTPt/preview.html

[5]http://www.spherelab.gatech.edu/

[6]http://en.wikipedia.org/wiki/NOx

[7]http://en.wikipedia.org/wiki/Greenhouse_gas

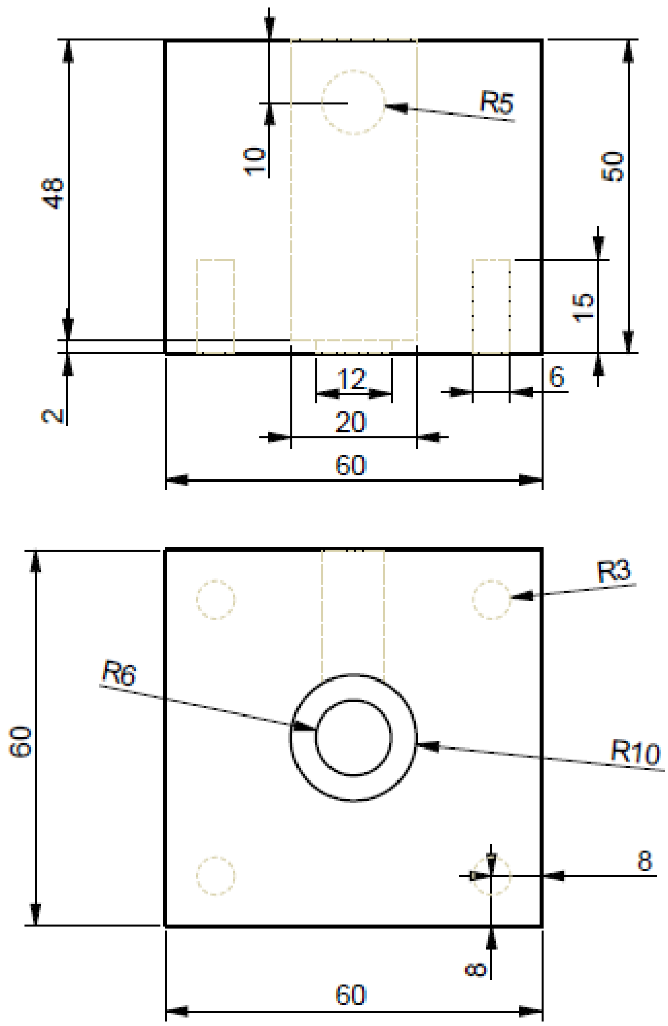
[8]http://en.wikipedia.org/wiki/Sustainability[]http://en.wikipedia.org/wiki/European_emission_standards

[9]http://www.electronics-tutorials.ws/transistor/darlington-transistor.html

[10] https://www.donaldson.com/en/engine/support/datalibrary/056798.pdf

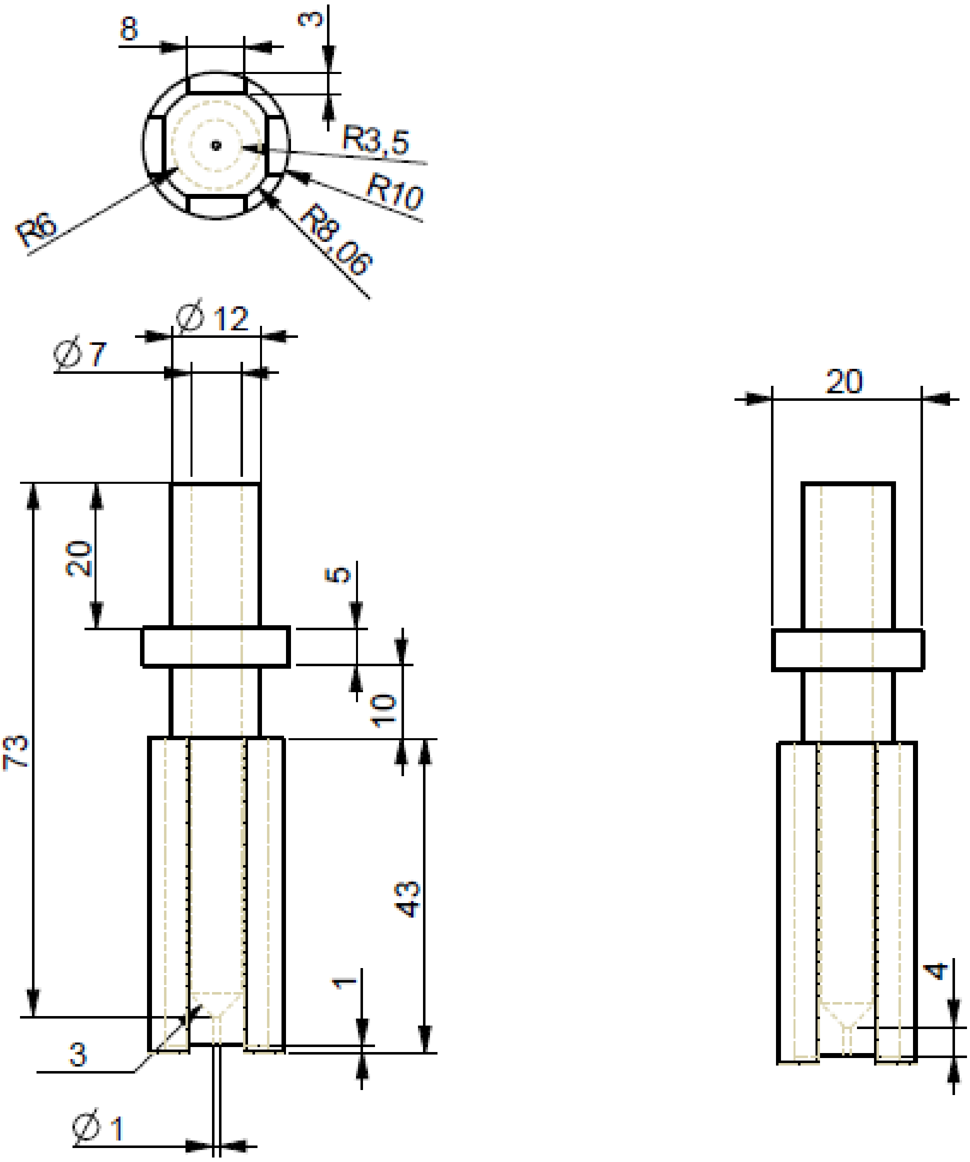
APPENDIX:

5.1 Injector Block Diagram:



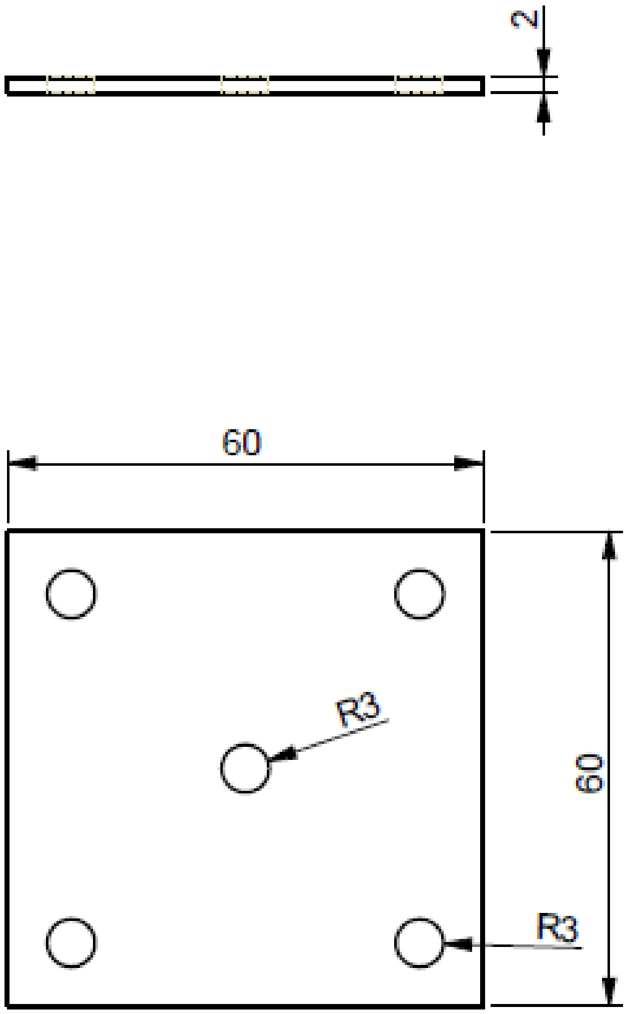
All dimensions are given in mm.

5.2 Injector Core Diagram:



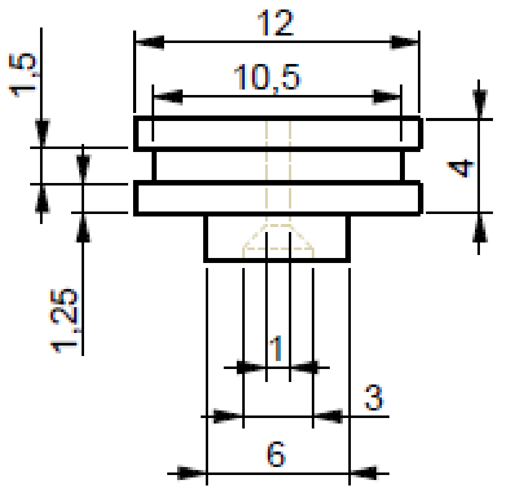
All dimensions are given in mm.

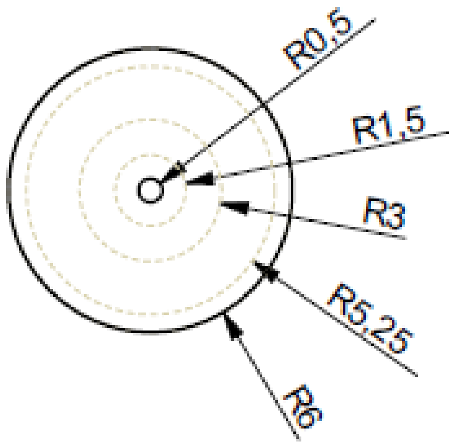
5.3 Front Plate Diagram:



All dimensions are given in mm.

5.4 Nose Cone Diagram:





All dimensions are in mm.